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Land Surface Temperature Measurements from EOS MODIS Data

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Abstract

A significant progress has been made in TIR instrumentation which is required to establish the spectral BRDF/emissivity knowledge base of land-surface materials and to validate the land-surface temperature (LST) algorithms. The SIBRE (spectral Infrared Bidirectional Reflectance and Emissivity) system and a TIR system for measuring spectral directional-hemispherical emissivity have been completed and tested successfully. Optical properties and performance features of key components (including spectrometer, and TIR source) of these systems have been characterized by integrated use of local standards (blackbody and reference plates). The stabilization of the spectrometer performance was improved by a custom designed and built liquid cooling system. Methods and procedures for measuring spectral TIR BRDF and directional-hemispheric emissivity with these two systems have been verified in sample measurements. These TIR instruments have been used in the laboratory and the field, giving very promising results. The measured spectral emissivities of water surface are very close to the calculated values based on well established water refractive index values in published papers. Preliminary results show that the TIR instruments can be used for validation of the MODIS LST algorithm in homogeneous test sites.

The beta-3 version of the MODIS LST software is being prepared for its delivery scheduled in the early second half of this year.

1. Recent Progress in TIR Instrumentation

TIR instrumentation is required to establish the spectral BRDF (bidirectional reflectance distribution function) and emissivity knowledge base of land-surface materials and to validate the MODIS Land-Surface Temperature (LST) algorithm. The BRDF/emissivity knowledge base is needed in the development of the generalized split-window LST algorithm [Wan and Dozier, 1995].

Our primary measurement instrument is a Zinc-Selenide (ZnSe) Fourier transform infrared spectrometer (FTIR). This unit is a stock model M2405-C made by MIDAC Corp. which has been fitted by MIDAC with a hi-color detector, a closed-cycle cryogenic cooler, and a more powerful mirror drive system. These three components are specially ordered by us in order to achieve the requirements for measuring the BRDF of land-surface materials. The detector is a wedge-sandwich of Mercury-Cadmium-Telluride (HgCdTe) and Iridium- Antimonide (InSb) elements. The wedge shape prevents the fluctuations in response that would otherwise result from parallel surfaces. The InSb element is sensitive to irradiance in the 2.5-6.0 micron region, and the HgCdTe element is sensitive in the 7-15 micron region, thus extending the instrument's response to all MODIS TIR bands of interest for Earth surface temperature measurements. The spectrometer was designed to be operated horizontally, but the instrumentation requires that the spectrometer be positioned over a range of angles for the BRDF measurements. The cryogenic cooler modification is a closed-cycle Helium refrigerator that allows operation of the spectrometer at any angle. The more powerful mirror drive system also allows operation at any angle without loss of the radiometric calibration accuracy.

To stabilize the instrument performance, a liquid cooling system was designed and built at UCSB. This system consists of a coolant pump, a radiator, and a copper sleeve (shown in Figure 1) that keeps the gas laser tube inside the MIDAC FTIR near ambient temperature. The working fluid is automotive antifreeze. With the laser tube temperature stabilized, the interferometer requires only an hour to stabilize after power-on. Tests show that otherwise, the instrument requires about ten hours to warm-p. This warm-uptime would be impractical in the field where power is supplied by a generator.

The noise equivalent differential temperature (NEAT) of the instrument was measured with the new detector and a CI blackbody made by CI Systems. The temperature resolution of the CI blackbody temperature controller is 0.01°C and its stability is specified better than 0.1°C. The NEAT was found to be 1-2°K in the 3.5-5μm spectral range, and 0.15°K in the 8-12μm range. These figures are for a single scan at a resolution of 4 cm^{-1}. The corresponding single scan signal-to-noise ratio (SNR) ranges from 20 at shorter wavelengths to 500 at longer wavelengths as the instrument views a blackbody surface at temperature 25°C. The effects of noise are reduced by averaging more than one scan. For instance, if 256 scans are averaged the NEAT becomes 0.1°K at 4μm and 0.01 'K at 10μm. The instrument was tested for calibration drift versus time and angle. The drift is less than 0.5% over the time periods of interest (about two minutes). The drift effects may be further reduced by averaging separate measurements of the same surface.

The integrating sphere FTIR system, as shown in Figure 2, consists of a 5 inch diameter Infragold Integrating Sphere (manufactured by Labsphere Inc.), a less expensive KBr FTIR Illuminator Spectrometer from MIDAC Corp. with the original liquid nitrogen cooled sandwich InSb/MCT detector and an internal TIR source at 1550 'K. The KBr FTIR has specifications similar to those of the stock model ZnSe FTIR mentioned above. We use gold mirror, diffuse gold plate, aluminum sheet, and pure water as local standards.

The active measurement of both the BRDF and the emissivity requires a thermal infrared (TIR) source. A 5-inch by 5-inch ceramic plate made by Infrasource was selected. This plate is positioned approximately 24 inches from the surface being measured. It has a high emissivity and can operate at temperatures up to 700 "K. To cancel background radiance effects, the source must be switched on and off. This is accomplished by a shutter plate that pivots to block the source illumination. The shutter is operated by a pair of solenoids driven by an digital sequencing system. The digital sequencing system drives the source shutter in synchronization with the FTIR scanning so that the on and off signals can be demodulated after measurement. Currently, it is set to switch every 64 scans, which is every eight seconds.

The Spectral Infrared Bidirectional Reflectance and Emissivity (SIBRE) instrument, as shown in Figure 3, is an integrated system that measures the BRDF and emissivity of natural surfaces in the laboratory or in the field. The instrument consists of the FTIR spectrometer, the shuttered infrared source, a reference plate, and a hemispherical pointing system. The hemispherical pointing system was designed and built by the UCSB physics machine shop. The structure consists of 2-inch diameter aluminum tubes rolled to the specified radius of 1.5 meters and welded into the hoop assemblies. The spectrometer carnage rolls along a double hoop and positions the spectrometer. The declination of the spectrometer is set manually and held in place with friction brakes. Alignment is by screw-jacks, which position the spectrometer to point to the center of the hemisphere. The pointing accuracy is specified to be one degree. There are mounting holes in the carnage to hold a thermal-electrically cooled (TEC) CI blackbody in front of the spectrometer for calibration. The double hoop with the spectrometer and carnage rolls along the horizontal hoop to set the relative azimuth between the spectrometer and the source. The source is mounted to a single hoop that is fixed in azimuth. The source declination is set by mounting the source arm in ***one*** of five positions along the single hoop. The entire system maybe disassembled for transportation and field use.

The reference plate assembly consists of a pivoting arm and a 10-inch square difuse gold plate (Infragold, manufactured by Labsphere Inc.). This plate swings over the sample area to provide a known reference during measurement of an unknown surface. The BRDF of the gold plate was determined by absolute radiometric measurements under controlled laboratory renditions. To do this, first, the spectral directional-hemispherical emissivity of the source was measured using our integrating sphere FTIR system. Next, the source was instrumented for temperature, and the radiance reflected by ***the*** gold plate was measured with the FTIR over the full range of source and detector angles. The temperature of the source and its emissivity provide the irradiance on the gold plate. An absolute calibration of the spectrometer gives the absolute reflected radiance of the plate. With geometrical considerations, these values can be converted to the plate BRDF. This process was repeated for each of the 163 geometries of the SIBRE instrument.

2. Methods for TIR BRDF and Emissivity Measurements

We use a differential ratio method to obtain the directional-semisphencal emissivity from the integrating sphere FTIR measurement data in the following two steps.

$$p_s(v) = \frac{Ss(v) - S_b(v)}{S_r(v) - S_b(v)} \times p_r(v) \tag{l-1}$$

$$E_s(v) = 1 - p_s(v) \tag{l-2}$$

where p(v) and e(v) are spectral reflectivit y and emissivity at wavenumber v, respectively. S_b, S_s, and S_r are spectral data for background, sample, and reference, respectively.

The SIBRE instrument measures BRDF at each geometrical configuration using the four-step method [Wan et al., 1994]. The four steps are to measure the reference with and without the source, and to measure the sample with and without the source. Since there is unknown irradiance from the background onto the surface, the source is switched on and off and the difference in radiance is used. This differencing cancels the background radiance and eliminates the need to find the intercept of the spectrometer calibration curve. Further, instead of computing the absolute irradiance difference from the source, the delta radiance measurements are made relative to the delta radiance of a reference plate with known BRDF. The ratio of the delta radiance of the unknown surface to the delta radiance of the known plate is multiplied by the BRDF of the known plate to obtain the BRDF of the unknown surface. Using this ratio also eliminates the need to find the spectrometer gain. The four step technique depends on the short-term stability of the instrument, of the background radiance, and of the sample temperature. Here, short-tern means changes over the measurement time of about two minutes.

A confounding element in the measurement of BRDF and emissivity in the infrared by this active technique is the unavoidable sample heating due to the source. This heating is negligible for conductive solids, but if the sample has a low thermal diffusivity it can be as large as several degrees Kelvin. Temperature changes of one-quarter degree Kelvin are significant. To correct for this, the source is cycled on and off during measurement. The difference signal is the average of the differences for each on-to-off and off-to-on transition. A further improvement in the accuracy of the difference is realized by fitting the signal temporal profile to a thermal heating model and evaluating the model at each transition point.

The spectrometer measures spectral radiance at a given angle. The source produces wideband infrared irradiance on the surface from another given direction. If the surface is isotropic, we need only measure the BRDF over the range of relative azimuths. Also, if the surface is symmetrical, we need only measure the relative azimuth from O to 180 degrees. Five source declinations were chosen based on the optimum points for a Gaussian quadrature integration of the BRDF (required to get the emissivity). Five detector declinations were chosen based on the MODIS look angle range. The azimuth points cover the circle at each source declination with equally spaced steps.

The characterization of one material sampIe produces 163 spectral measurements of the sample, and 163 measurements of the reference plate. The first step in processing the spectra is generating the delta values. Next, these delta values are converted to BRDF by multiplying their ratios by the BRDF of the reference plate. These 163 BRDF measurements cover the quarter-sphere. Finally, the BRDF files are integrated for each detector declination to give five spectral emissivity curves. The BRDF and emissivity data are stored at the full 4 cm^{-1} resolution, but reduced sets will be extracted by convoluting these with the MAS and MODIS spectral band responsivities.

After making correction for the sample heating, the four-step method is expressed as

$$f_s = \frac{S_{s-on} - S_{s-off}}{S_{r-on} - S_{r-off}} \times f_r \quad . \tag{2-1}$$

Where f_s and f_r are BRDF for sample and reference, respectively. $S_{s\text{-}on}$ and $S_{s\text{-}off}$ are spectra of the sample with and without the source; and S_{r-on} and $S_{r\text{-}off}$ are spectra of the reference plate with and without the source. Then sample emissivity can be obtained by Kirchhoff's law

$$\varepsilon(\mu) = 1 - \int_0^{2\pi} \int_0^1 f(\mu, \mu', \phi) \mu' d\mu' d\phi \quad . \tag{2-2}$$

3. Methods for Surface Temperature Measurements

Surface temperatures in the field are necessary to validate the LST algorithms during concurrent overpasses by MAS and MODIS. Surfaces suitable for this validation include various land cover types and water. Once land-surface emissivity is determined by using the SIBRE or the integrating sphere, land surface temperatures can be measured with the FTIR spectrometer atop a tripod (as shown in Figure 4) and with a wideband IR radiometer (an Everest IR thermometer). As shown in Figure 4, the FTIR spectrometer atop a tripod can view the land surface or the CI blackbody through the gold mirror in the front. The blackbody can swing in or out the field-of-view of the spectrometer. Water temperatures can be also measured with contact sensors just beneath the water surface. Land surface temperatures can vary widely spatially and temporally, so measurements will be taken over as large an area as possible. Our wideband radiometer can be moved quickly for multiple measurements, and it is inexpensive, so additional units are planned.

To obtain the kinetic temperature of a surface we measure the total surface-leaving radiance. Then, the portion of this total that is the reflected downwelling radiance is subtracted. This calculation requires the surface reflectivity and the downwelling radiance. The surface reflectivity is measured independently using the SIBRE or the integrating sphere. The downwelling radiance is obtained by measuring the radiance from a piece of crumpled aluminum foil or the diffuse gold plate. Finally, the remaining emitted radiance is converted to temperature using the surface emissivity and the Planck function.

This process is feasible for both the spectral and the wideband instruments. We can do both in the field. For the spectral instrument, the result is an estimate of the kinetic temperature at each spectral bin. Ideally, these should all be the same, but they will not be because of noise. To obtain the temperature estimate, the values will be averaged, weighted by the signal-to- noise ratio of each bin. For the wideband instrument, the temperature estimate results from calculations based on measurement data.

Both the spectral and the wideband instrument require an absolute calibration before the surface is measured. This is achieved using a radiance profile generated with a temperature-controlled blackbody. The blackbody plate has a known temperature and known emissivity. Together with a nominal background temperature and emissivity, the radiance seen by the sensor can be calculated for a range of temperatures. These readings together with the raw sensor readings provide data for a linear or quadratic calibration. Then, after the readings of the surface are taken they are converted to absolute radiance with the calibration formula.

4. Preliminary Results

The spectral emissivity of water surface measured with our integrating F'TIR system is very close to the calculated values based on well established method and water refractive index values in published papers [Masuda et al, 1988; Hale and Querry, 1973]. As shown in Figure 5, the RMS difference between the measured and calculated spectral emissivities in the wavenumber range 650-3000cm^{-1} is 0.002, if 9 sets of 512 measured spectra are used. This RMS difference can be reduced by increasing the number of measured spectra.

The spectral emissivities of sands measured with the integrating sphere and SIBRE systems are shown in Figure 6. They agree very well except in the wavenumber ranges 1000-2000 cm^{-1} and above 2400 cm-l, where there are peaks in the sample reflectance. According to Eq. 1-1 and 2-1, the relative error in sample reflectivity is proportional to the relative error in reference reflectivity. So the absolute error in sample reflectivity is proportional to the absolute value of the sample reflectivity. In order words, the absolute error in sample emissivity is smaller as the sample emissivity increases. Sands may be the terrestrial material which has largest TIR reflectivity. But in the wavenumber range where MODIS bands 31 and 32 are located, the sands reflectivity is smaller than 0.05 so its emissivity is larger than 0.95 and the integrating sphere and SIBRE systems give very close measurement values.

Spectral emissivity measurements were also made for different soil and vegetation leave samples. All these results indicate that our TIR instruments can be used to validate the MODIS LST algorithm.

5. Beta-3 Delivery of the MODIS LST Code

The MODIS LST algorithm has been developed. Toolkit software packages of Product Generation System (PGS) and MODIS Application Program Interface (M-API) have been implemented on local SCF (Science Computing Facility) DEC Alpha workstations. The beta-3 version of the MODIS LST code is being prepared for its delivery scheduled in the early second half of this year.

6. Anticipated Future Actions

The TIR instruments and local calibration standards will be further improved for their NIST traceability. The procedures of TIR measurements and data processing will be refined to reduce the errors in the final results of BRDF and emissivity. Two papers on TIR BRDF/emissivity measurements will be submitted to referred journals shortly. The work to establish TIR BRDF/emissivity knowledge base and the development of MODIS LST algorithm will be continued. Field campaign using the TIR instruments with concurrent overpasses by MAS and AVHRR has been planned in order validate the MODIS LST algorithm.

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Wan, Z. and J. Dozier, "A generalized split-window algorithm for retrieving land-surface temperature from space," *IEEE Trans. Geosci. Remote Sens.*, submitted 1995.

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Figure 1, The MIDAC FTIR with the liquid cooling system.

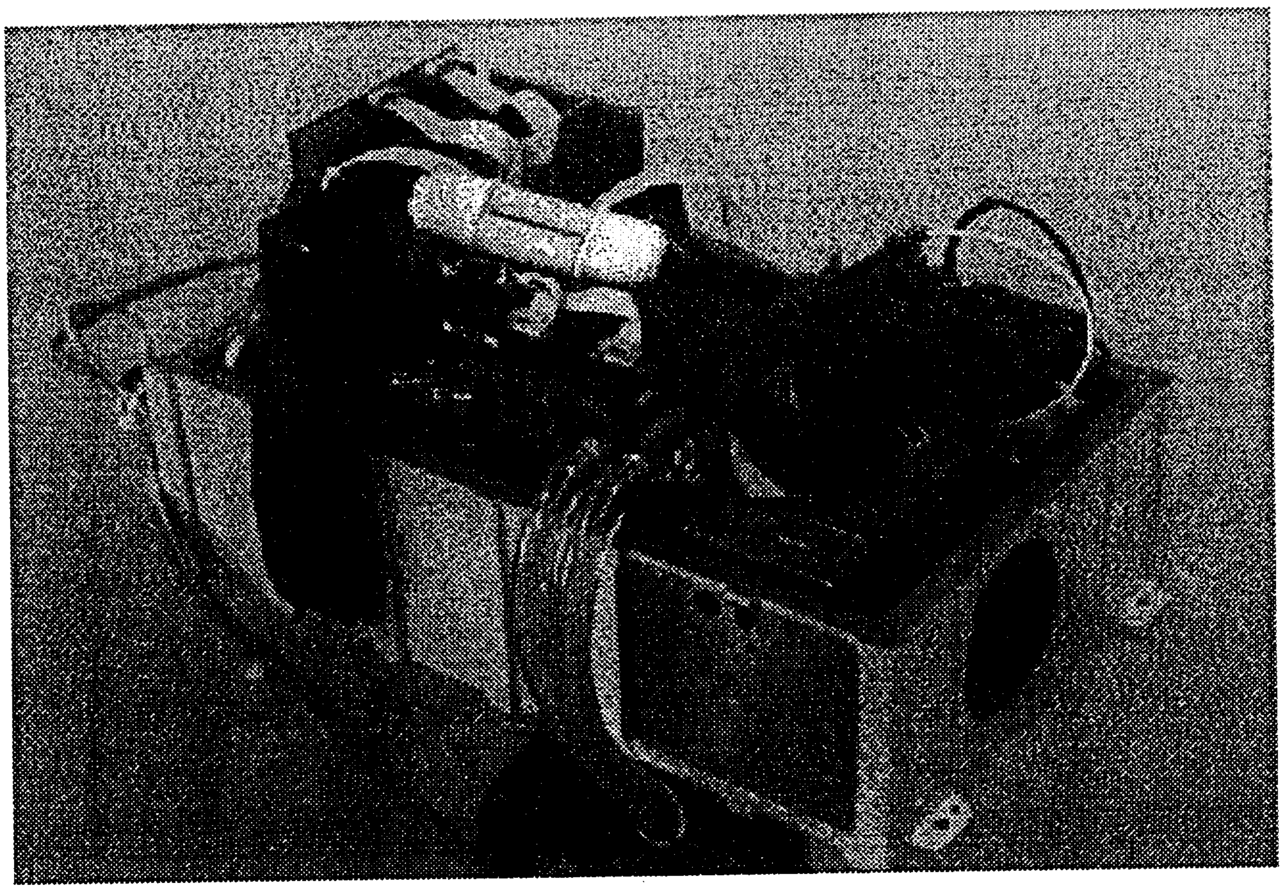


Figure 2, Integrating Sphere FTIR system.

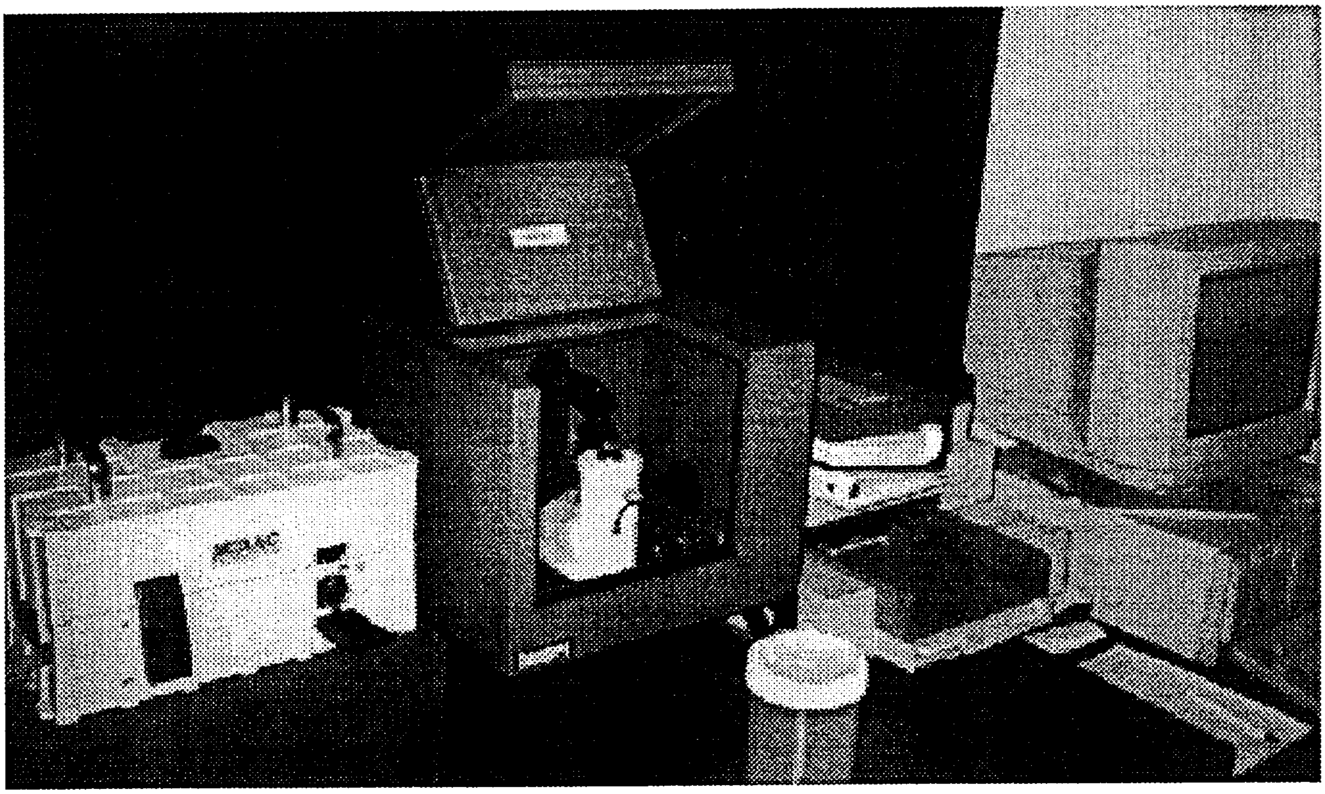


Figure 3, The Spectral Infrared Bidirectional Reflectance and Emissivity (SIBRE) system.

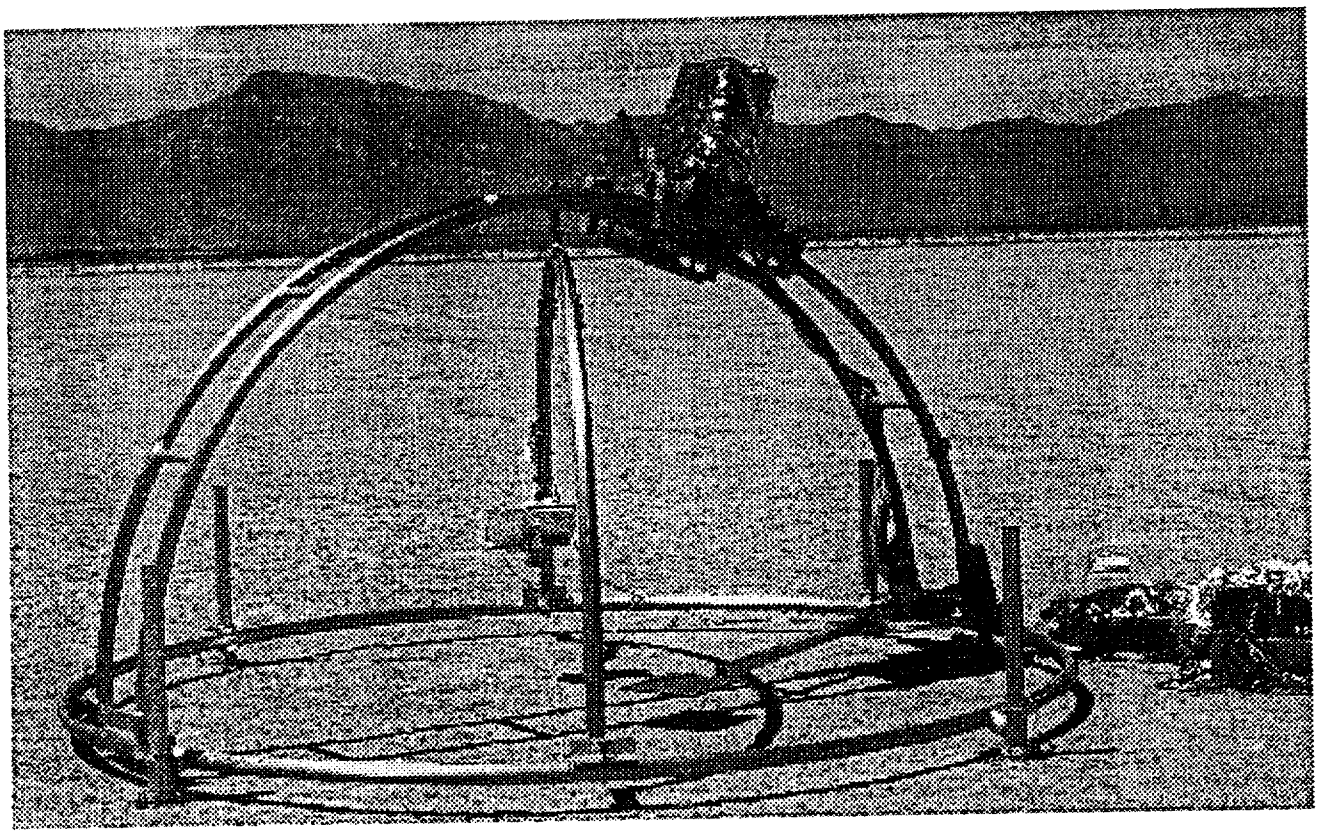
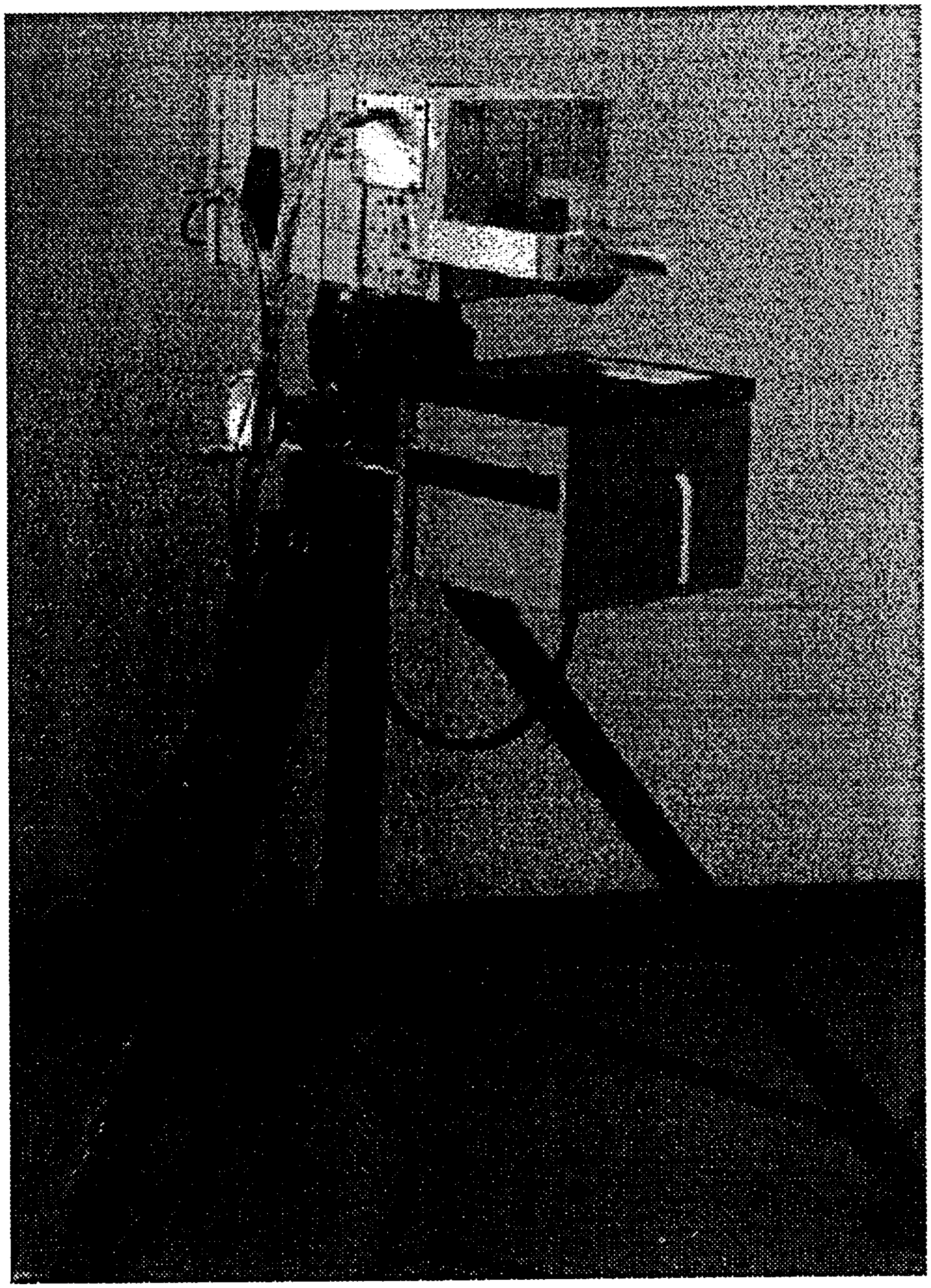


Figure 4, The FTIR spectrometer and CI blackbody atop a tripod.



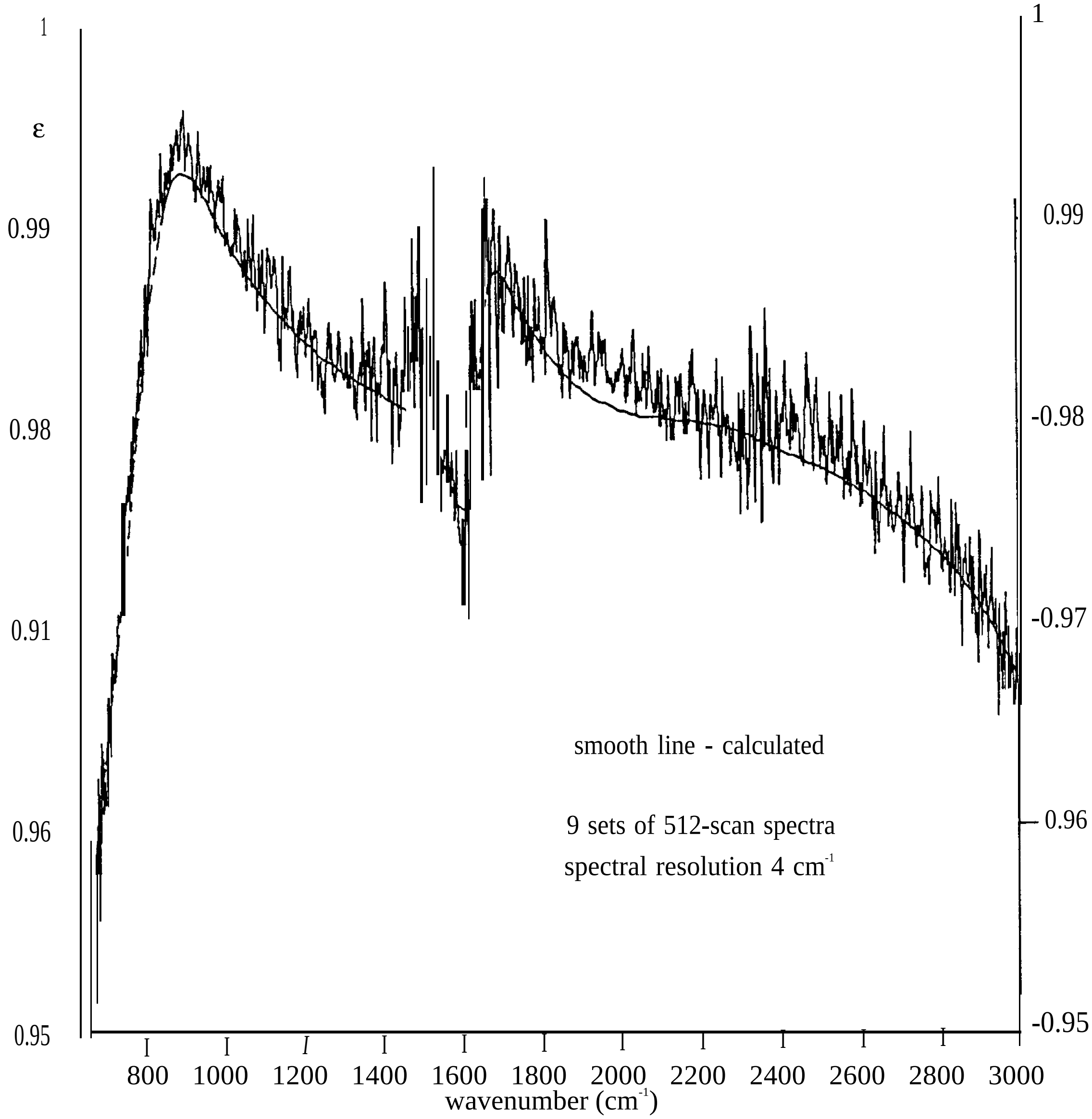


Figure 5. Measured and calculated spectral emissivities of water surface.

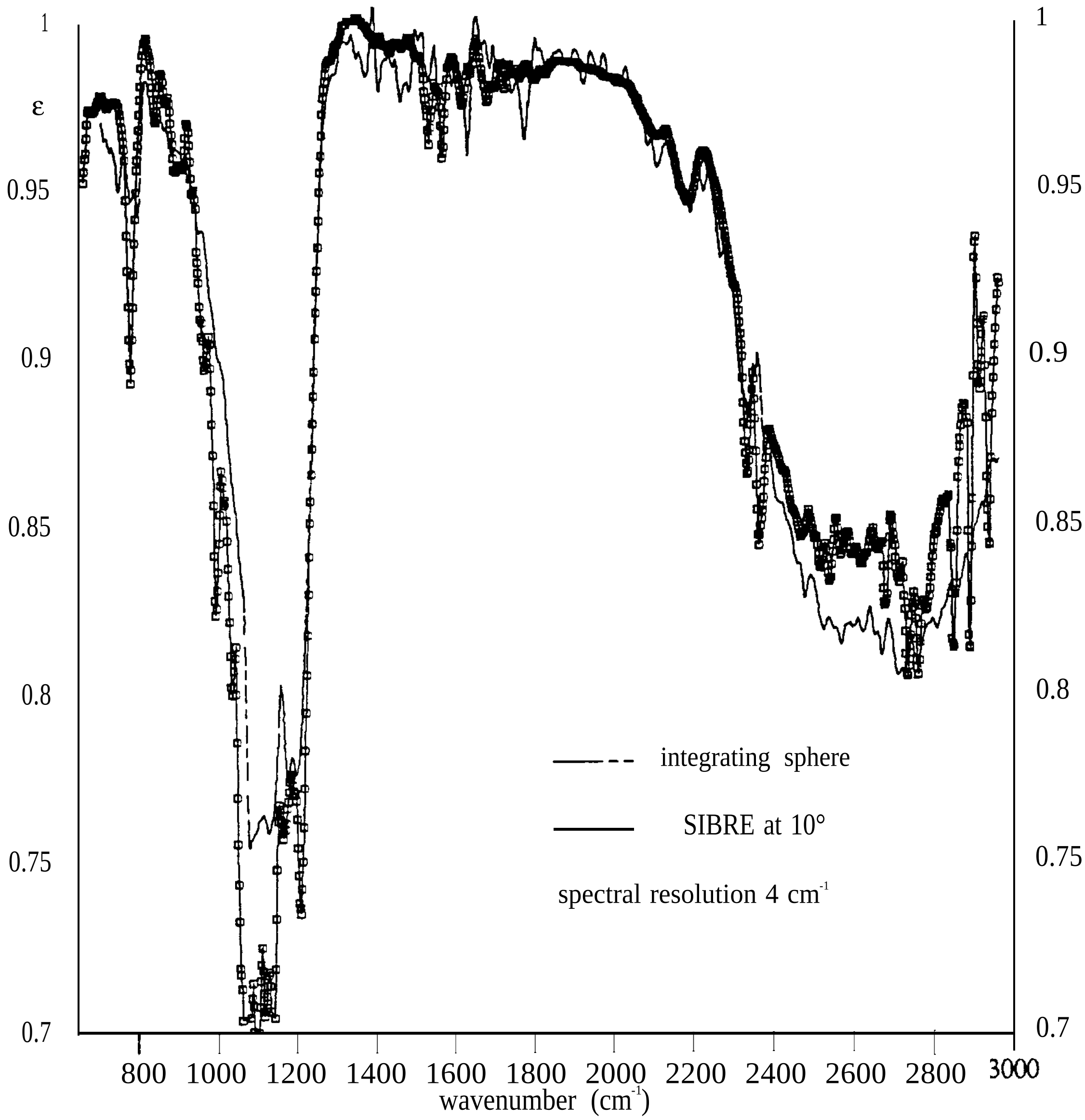


Figure 6. Spectral emissivities of sands measured with the integrating sphere and SIBRE systems.